Woodhead Publishing Series in Energy: Number 25

Advanced membrane science and technology for sustainable energy and environmental applications

Edited by

Angelo Basile and Suzana Pereira Nunes



Oxford Cambridge Philadelphia New Delhi

Contents

Contrib	utor contact details	xv
Woodhe	ead Publishing Series in Energy	xxi
Preface		xxvii
Part I	Introduction to membrane science and engineering	
1	Fundamental membrane processes, science and engineering V. Calabrò, University of Calabria, Italy and A. Basile, Institute on Membrane Technology of the Italian National Research Council (ITM-CNR), Italy	3
1.1	Introduction	3
1.2	Membrane processes	4
1.3	Conclusions and future trends	18
1.4	References	18
2	Fundamental science of gas and vapour separation in polymeric membranes Y. Yampolskii, A.V. Topchiev Institute of Petrochemical Synthesis, Russian Academy of Sciences, Russia	22
2.1	Introduction	22
2.2	Basic principles and definitions of separation processes	23
2.3	Effects of the properties of penetrants and polymers	32
2.4	Effects of pressure on transport parameters	39
2.5	Effects of temperature on transport parameters	45
2.6	Gas permeability of polymers: objects of membrane gas	
0	separation	47
2.7	References	49
2.8	Appendix: list of symbols	54

VI	Contents	
3	Characterization of membranes for energy and environmental applications M. Campo, A. Tanaka and A. Mendes, University of Porto, Portugal and J. M. Sousa, University of Trás-os-Montes e Alto Douro, Portugal	56
3.1	Polymer and carbon molecular sieve membranes	56
3.2	Zeolite and mixed matrix membranes	64
3.3	Mass transport characterization	71
3.4	Conclusions	80
3.5 3.6	References A propodicy list of symbols	80
3.0	Appendix: list of symbols	88
4	Economic analysis of membrane use in industrial applications V. CALABRÒ, University of Calabria, Italy and A. BASILE, Institute on Membrane Technology of the Italian National Research Council (ITM-CNR), Italy	90
4.1	Introduction	90
4.2	Economic analysis	91
4.3	Case studies	96
4.4	Conclusions and future trends	106
4.5	References	107
Part II	Membranes for coal and gas power plants: carbon dioxide (CO_2) capture, synthesis gas processing and oxygen (O_2) transport	
5	Membrane technology for carbon dioxide (CO ₂)	
	capture in power plants	113
	A. BASILE, A. GUGLIUZZA, and A. IULIANELLI, Institute on Membrane Technology of the Italian National Research Council (ITM-CNR), Italy and P. MORRONE, University of Calabria, Italy	
5.1	Introduction	113
5.2	Reasons for using membranes for carbon dioxide (CO ₂) separation and sequestration	123
5.3	A short review of membrane technology for CO ₂ separation	123
5.4	Performance of membrane processes for CO ₂ sequestration	137
5.5	Membrane modules for CO ₂ sequestration	139
5.6	Design for power plant integration	141
5.7	Cost considerations and membrane technology at the	
	industrial scale	142
5.8	Modelling aspects of gas permeation membrane modules	144
5.9	Conclusion and future trends	150

	Contents	Vii
5.10 5.11	References Appendix: list of symbols	151 158
6	Polymeric membranes for post-combustion carbon dioxide (CO ₂) capture W. Yave and A. Car, GKSS-Research Centre Geesthacht GmbH, Germany	160
6.1 6.2 6.3 6.4 6.5 6.6 6.7	Introduction Basic principles of flue gas membrane separation Membrane development and applications in power plants Operation and performance issues and analysis Advantages and limitations Future trends References	160 163 166 176 179 179
7	Inorganic membranes for pre-combustion carbon dioxide (CO ₂) capture A. IULIANELLI and A. BASILE, Institute on Membrane Technology of the Italian National Research Council (ITM-CNR), Italy and H. LI and R. W. VAN DEN BRINK, ECN Hydrogen Production and CO ₂ Capture, The Netherlands	184
7.1	Introduction	184
7.2 7.3	Inorganic membranes for carbon dioxide (CO ₂) separation Membrane reactors for CO ₂ capture	187 197
7.4	Techno-economic analysis of the integrated gasification combined cycle (IGCC) and natural gas combined cycle	
7 -	(NGCC)	205
7.5 7.6	Conclusions and future trends References	207 207
8	Inorganic membranes for synthesis gas processing S. SMART, L. P. DING and J. C. DINIZ DA COSTA, University of Queensland, Australia	214
8.1	Introduction	214
8.2	Basic principles of membrane operation	218
8.3	Membrane materials and development	223
8.4	Application and integration in industry	230
8.5	Membrane modules	237
8.6	Future trends	241
8.7	Conclusions	244
8.8	References	244
8.9	Appendix: list of symbols	253

v i ii	Contents	
9	Oxygen transport membranes: dense ceramic membranes for power plant applications S. SMART and J. C. DINIZ DA COSTA, University of Queensland, Australia, and S. BAUMANN and W. A. MEULENBERG, Forschungszentrum Jülich, Germany	255
9.1	Introduction	255
9.2	Oxygen transport membrane materials, development and	
	design	256
9.3	Principles of oxygen membrane separation	263
9.4	Application and integration in power plants	267
9.5	Oxygen transport membranes	275
9.6	Future trends	282
9.7	Conclusions	284 285
9.8	Acknowledgements	286
9.9	References	200
Part III	Membranes for the petrochemical industry: hydrocarbon fuel and natural gas processing, and advanced biofuels production	
10	Membranes for hydrocarbon fuel processing and separation	295
	A. Gugliuzza, A. Iulianelli and A. Basile, Institute on Membrane Technology of the Italian National Research Council (ITM-CNR), Italy	200
10.1	Introduction	295
10.2	Membrane materials, development and design for	
	hydrocarbon processing	297
10.3	Separation of olefins and paraffins	314
10.4	Removal of hydrocarbons from liquid streams	317
10.5	Nanotechnologies from fundamental research to large-scale	
	industry	322
10.6	References	329
10.7	Appendix: list of symbols	338
11	Polymeric membranes for natural gas processing S. E. Kentish, CRC for Greenhouse Gas Technologies (CO2CRC), University of Melbourne, Australia	339
11.1	Introduction	339
11.2 11.3	Polymeric membrane operations in natural gas processing Membrane materials, development and design for natural	339
•	gas processing	341
11.4	Operation and performance issues and analysis	346

	Contents	ix
11.5 11.6	Application and integration into natural gas operations Advantages and limitations	349 351
11.7	Future trends	352
11.8	Sources of further information and advice	355
11.9	References	356
11.10	Appendix: list of symbols	360
12	Membranes for advanced biofuels production S. Curcio, University of Calabria, Italy	361
12.1	General overview of second-generation biofuels	361
12.2	Hydrolysis of biomass to produce sugars	367
12.3	Key role of process engineering for second-generation	251
10.1	biofuels production	371
12.4	Membrane bioreactors	372
12.5	Biocatalyst continuously separated by a membrane system	25.4
	and recirculated into the reaction tank	374
12.6	Biocatalyst immobilized onto the membrane surface	378
12.7	Continuous stirred tank reactor with biocatalyst	
	immobilized on the membrane surface (CSTMB)	382
12.8	Single pass membrane bioreactor	384
12.9	Hollow fibre membrane bioreactor with recycling of	
	unreacted substrate	396
12.10	Conclusions	402
12.11	Sources of further information and advice	403
12.12	References	403
12.13	Appendix: list of symbols	406
Part IV	Membranes for alternative energy applications: batteries, fuel cells and hydrogen (H_2) production	
13	lon exchange membranes for vanadium redox flow batteries	413
	S. S. HOSSEINY, Aachener Verfahrenstechnik-Chemische Verfahrenstechnik, RWTH-Aachen University, Germany and M. WESSLING, Aachener Verfahrenstechnik-Chemische Verfahrenstechnik, RWTH-Aachen University, Germany and University of Twente, The Netherlands	
13.1	Electrochemical energy storage	413
13.2	Vanadium redox flow batteries	418
13.3	Membranes	423
13.4	Conclusions	430
13.5	References	430

14	Membranes for lithium batteries R. Bongiovanni and J. R. Nair, Politecnico di Torino, Italy, C. Gerbaldi, Italian Institute of Technology and Politecnico di Torino, Italy and A. M. Stephan, Central Electrochemical Research Institute, India	435
14.1	Introduction	435
14.2 14.3	Types of lithium battery and basic operating principles Polymer electrolyte membranes for advanced lithium	436
	batteries	441
14.4	Conclusions and future trends	455
14.5	Sources of further information and advice	456
14.6	References	458
15	Proton exchange membranes for fuel cells V. Arcella, L. Merlo and A. Ghielmi, Solvay Solexis S.p.A., Italy	465
15.1	Introduction	465
15.2	Basic operating principles and types of fuel cell	466
15.3	Membrane materials, design and fabrication processes	468
15.4	Membrane performance in operation: issues and analysis	487
15.5	Integration and application of proton exchange membrane	490
156	(PEM) fuel cell systems	489
15.6 15.7	Advantages and limitations of PEM fuel cells	491
15.7	Future trends	491
	Sources of further information and advice	492
15.9	References	492
15.10	Appendix: list of symbols	494
16	Functional ceramic hollow fibre membranes for catalytic membrane reactors and solid oxide fuel	
	cells	496
	Z. T. Wu, M. H. D. OTHMAN, B. F. K. KINGSBURY and K. LI, Imperial College London, UK	
16.1	Introduction	496
16.2	Membrane materials issues	499
16.3	Membrane development routes and macrostructure control	501
16.4	A multifunctional dual-layer hollow fibre membrane	501
	reactor (DL-HFMR) for methane conversion	507
16.5	Dual-layer hollow fibres for a micro-tubular solid oxide	507
10.5	fuel cell (SOFC)	510
16.6	Other ways of improving ceramic dual-layer hollow	518
10.0	fibres	525
16.7	Conclusions	535
16.8	References	537
10.0	References	538

	Contents	хi
17	Proton-conducting ceramic membranes for solid oxide fuel cells and hydrogen (H ₂) processing W. A. Meulenberg, M. E. Ivanova, Forschungszentrum Jülich GmbH, Germany, J. M. Serra, Instituto de Technologia Química (UPV-CSIC), Spain and S. Roitsch, Ernst-Ruska Centre for Microscopy and Spectroscopy with Electrons, RWTH Aachen University and Forschungszentrum Jülich GmbH, Germany	541
17.1	Introduction	541
17.2	Operation principle of proton-conducting ceramic	
	membranes and demands on materials	542
17.3	Protons and proton conductance in ceramics	545
17.4	Conductivity and hydrogen (H ₂) flux of selected classes of ceramic membrane materials	549
17.5	Structure of selected classes of proton-conducting	
	materials	555
17.6	Chemical stability of selected classes of ceramic	
	membrane materials	559
17.7	Conclusions	561
17.8	Acknowledgements	562
17.9	References	562
18	Membrane electrolysers for hydrogen (H ₂) production P. MILLET, University of Paris, France	568
18.1	Introduction	568
18.2	Basic principles of electrolysis	571
18.3	Membrane materials	574
18.4	Membrane performance	580
18.5	Application and integration of electrolyser systems	586
18.6	Some advantages and limitations of current membrane	
	materials	601
18.7	Future trends	605
18.8	Sources of further information and advice	605
18.9	References	606
18.10	Appendix: nomenclature	608
19	Piomimotic membrane reactors for hydrogen (U.)	
19	Biomimetic membrane reactors for hydrogen (H ₂)	610
	production S. Bensaid and G. Saracco, Politecnico di Torino, Italy	610
19.1	Introduction	610
19.2	General background to the concept	613
19.3	An ambitious goal with numerous challenges	614
19.4	Thermodynamic limitations and device design	622
19.5	Integrated engineering approach for solar-to-fuel	

635

conversion

xii	Contents	
19.6 19.7	Conclusions References	638 640
Part V	Membranes for industrial, environmental and nuclear applications	
20	Membranes for industrial microfiltration and ultrafiltration A. Cassano and A. Basile, Institute on Membrane Technology of the Italian National Research Council (ITM-CNR), Italy	647
20.1	Introduction	647
20.2 20.3	Basic principles of microfiltration and ultrafiltration Membrane materials and membrane preparation	648
	technology	649
20.4	Module configuration and process design	652
20.5	Concentration polarization and membrane fouling	661
20.6	Applications	668
20.7	Microfiltration and ultrafiltration in integrated processes	673
20.8	Advantages and limitations	676
20.9	Future trends	676
20.10	Sources of further information and advice	677
20.11	References	677
21	Membranes for forward osmosis in industrial applications N. K. RASTOGI and C. A. NAYAK, Central Food Technological Research Institute, India	680
21.1	Introduction	680
21.2	Mechanism of forward osmosis	683
21.3	Membranes for forward osmosis	688
21.4	Forward osmosis membrane modules	692
21.5	Effect of various parameters on transmembrane flux	695
21.6	Applications of forward osmosis	703
21.7	Conclusions	711
21.8	Acknowledgements	712
21.9	References	712
22	Degradation of polymeric membranes in water and wastewater treatment A. Antony and G. Leslie, The University of New South Wales, Australia	718
22.1	Introduction	718
22.2	Polymer materials and module design	719

	Contents	XIII
22.3	Membrane failure and operational issues	720
22.4	Membrane degradation mechanisms	724
22.5	Identification and monitoring of membrane degradation	731
22.6	Materials degradation control strategies	737
22.7	Future trends	739
22.8	Sources of further information and advice	739
22.9	Acknowledgements	740
22.10	References	740
23	Membranes for photocatalysis in water and	
	wastewater treatment	746
	V. LODDO and L. PALMISANO, Università di Palermo, Italy and T. MARINO and R. MOLINARI, Università della Calabria, Italy	
23.1	Introduction	746
23.2	Basic principles of heterogeneous photocatalysis	747
23.3	Membrane materials developments and design for	
	photocatalysis	749
23.4	Membrane operations performance issues and analysis:	
	case studies	759
23.5	Future trends	765
23.6	Sources of further information and advice	765
23.7	References	765
24	Membranes for nuclear power applications S. Tosti, ENEA, Italy and C. Rizzello, Tesi Sas, Italy	769
04.1	•	760
24.1	Introduction	769
24.2	Membranes for nuclear fission applications	771
24.3	Membranes for nuclear fusion applications	776
24.4	Conclusions	785
24.5	Future trends	787
24.6	References	788
	Index	<i>7</i> 92